

# **Analytical and Numerical Studies of Active and Passive Microwave Ocean Remote Sensing**

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## **LONG-TERM GOALS**

The long term goals of this project involve developing improved understanding of sea surface thermal emission and scattering through the application of both analytical and efficient numerical methods for electromagnetics and hydrodynamics. New insights regarding these phenomena can then be applied to improve microwave active and passive remote sensing of the ocean surface.

## **OBJECTIVES**

NRL's WindSAT, scheduled for launch in 2002, will place a polarimetric microwave radiometer into orbit for the first time. Using WindSAT measured brightness temperatures to retrieve sea surface wind speed and direction requires an understanding of the relationship between sea surface emitted microwave power and sea conditions. Analytical theories have been developed for the prediction of microwave sea surface brightness temperatures and have shown some success, but differences among the theories proposed and the limited amount of current data still makes the underlying physics unclear. Project efforts in emission theory are focused on studies and extension of the analytical models to provide improved understanding of the phenomena producing emission signatures. Development of efficient numerical models for emission predictions has also been initiated, and a web-site ([esl.eng.ohio-state.edu/~rsttheory/windsat.html](http://esl.eng.ohio-state.edu/~rsttheory/windsat.html)) has been created to serve as a central location for the sea emission modeling community.

A DURIP project for development of an ultra-wideband radiometric sensor was also completed this FY to provide a system for experimental confirmation of project theoretical predictions.

The development of improved models for scattering from the sea surface has been another focus of the project. Although standard approximate models exist for active sensing of the sea surface, several issues regarding the physical scattering mechanisms and effect of non-linear hydrodynamics remain a subject of debate. This project applies numerically exact models to avoid the limitations of approximate methods so that the influence of different scattering mechanisms can be established. Radar image formation, Doppler analysis, and detailed comparisons with standard approximate theories are used as tools to help understand the scattering process.

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## **APPROACH**

Analytical model studies of sea surface emission are focusing on the small-slope theory [1]-[4]. An extensive debate in the community is currently taking place with regard to the source of azimuthal harmonic variations of ocean brightness temperatures, particularly the relative influence of large and small scale wave structures. Uncertainties in the ocean surface directional spectrum and in long-short wave hydrodynamic modulations make this a difficult question to resolve conclusively, but studies of emission theories can reveal the extent to which asymmetry in differing length scales can contribute to observed harmonics independent of the directional spectrum model used. Insights obtained from previous project studies have shown that nadir observing, multiple frequency brightness temperature measurements offer a potential means of remote sensing the sea surface curvature spectrum; to experimentally demonstrate this concept, a DURIP project was awarded for development of an ultra-wideband radiometer. This sensor was delivered in Nov 2001, and has been applied in initial near-nadir measurements of rough surface profiles [5], as well as limited tests of sub-surface object sensing [6].

The approach to the scattering problem is to apply recently developed numerical models for scattering [7] and hydrodynamic evolution [8]-[9] of both two and three dimensional rough sea surfaces. Earlier studies in the grazing angle regime have shown the importance of including non-linear hydrodynamic effects in the sea surface model, since “sea spike” like behaviors are not captured by standard linear surface models. Numerical approaches to the hydrodynamic surface evolution are therefore being applied, with scattering results compared under differing approximate hydrodynamic methods to determine the influence of these models [10]-[11]. Comparisons with analytical scattering theories, such as the small slope approximation, IEM, and composite surface model, are also being pursued to assess the performance of these techniques [12].

## **WORK COMPLETED**

Several new developments have occurred in FY 02. Analytical expressions for a fourth order small slope theory of sea surface emission have been developed [13]. The reduction of these results to the optical limit has been confirmed, and continues to demonstrate the effectiveness of optically based theories in the “large scale” surface limit. At present, efforts to compute long-short wave interaction effects efficiently are in progress; once evaluated these results will provide the first appropriate assessment of “tilting” effects computed in the widely-used “two scale” model. A by-product of this research is a simple approximation of the “two scale” model that requires only three double integrals as opposed to the standard quadruple integration, while still including long/short wave tilting effects.

A numerical study of higher order optical and small slope theories has also been performed for a simple bi-sinusoidal surface [14]. This study confirms that the small slope theory can capture shadowing and multiple-scattering effects if computed to a sufficiently high order, although analytical expressions for terms higher than fourth order will likely not be practical. Finally, the sea emission modeling web page has been continually maintained and updated to provide a location for comparisons of model implementations by members of the emission modeling community.

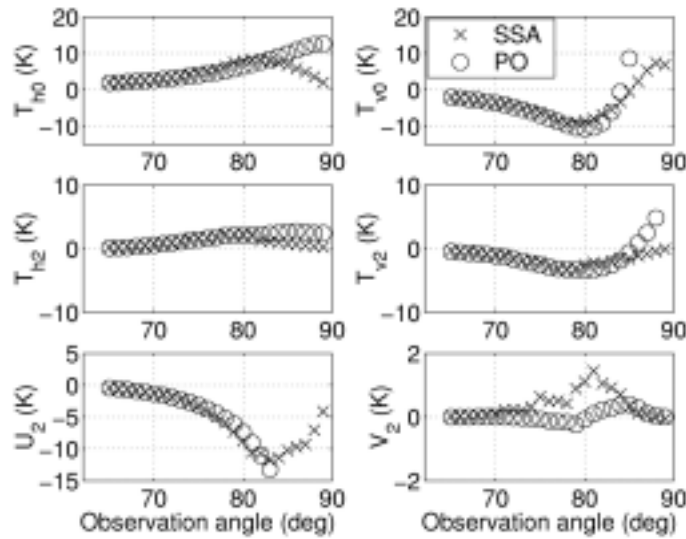
The DURIP multi-frequency radiometer (MFRAD) was delivered to OSU by Radiometrics, Inc. of Boulder, CO in Nov 2001. The 37 channel system operating between 2 and 18 GHz has been used in some initial measurements of periodic surface brightnesses [5] and sub-surface objects [6]. An antenna system for use in near-nadir observations was also developed. Results with the periodic surface study

confirm the sensitivity of near-nadir brightness measurements to the spectrum of the observed surface.

Active sea remote sensing studies in FY02 have continued use of combined numerical electromagnetic and hydrodynamic models to investigate backscattered field Doppler spectra. To address instability problems in the hydrodynamic simulations, a simple “curvature filter” approach has been developed to suppress the growth of steep short wave features [11]. Use of this filter has allowed L-band Monte Carlo backscattering simulations with non-linear sea surfaces at wind speeds up to 5 m/s, as opposed to the previous limit of 2 m/s. Several tests were performed to investigate the influence of the curvature filter; the results suggest that the effect of the filter on backscattered Doppler spectra is minimal. Results show a continued broadening of the Doppler spectrum as the wind speed increases, along with increased polarization dependence at the higher windspeeds.

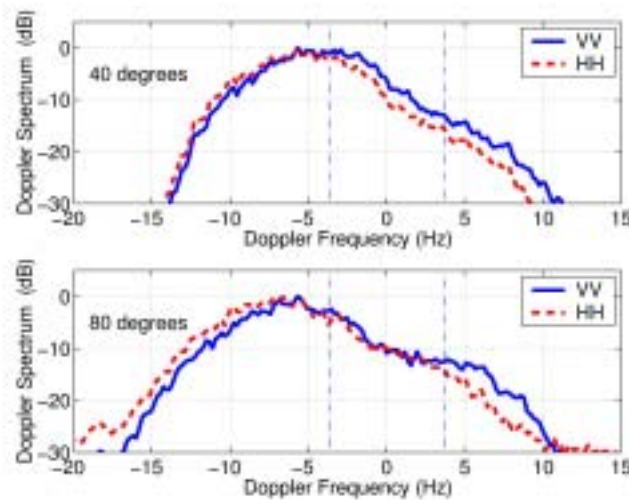
## RESULTS

Figure 1 illustrates results from the numerical study of polarimetric thermal emission from a bi-sinusoidal surface (i.e.,  $z = \sin(2\pi x/P_x)\sin(2\pi y/P_y)$ ) [14]. In this study, a numerical implementation of the small slope approximation was used that allowed computations up to twentieth order in surface slope. Results were compared with a numerical “multiple scattering” optical theory that approximately included interactions between surface points up to the tenth order. The surface used in Figure 1 has periods of 50 by 100 wavelengths and an amplitude of 1.5 wavelengths, so that an optical theory should be appropriate and so that small surface slopes (maximum 0.19) are retained. A sea water dielectric constant at 19 GHz is used. Results illustrate zeroth and second azimuthal harmonic coefficients of the four polarimetric brightnesses versus polar observation angles from 65 to 89 degrees; in this region both shadowing and multiple scattering effects should be important. The comparison shows the optical and SSA models to be in agreement for polar angles less than approximately 70 degrees, while the optical model yields inaccurate results at the larger angles. These comparisons confirm the ability of the SSA model to capture shadowing and multiple scattering effects if terms of a sufficiently high order are included.



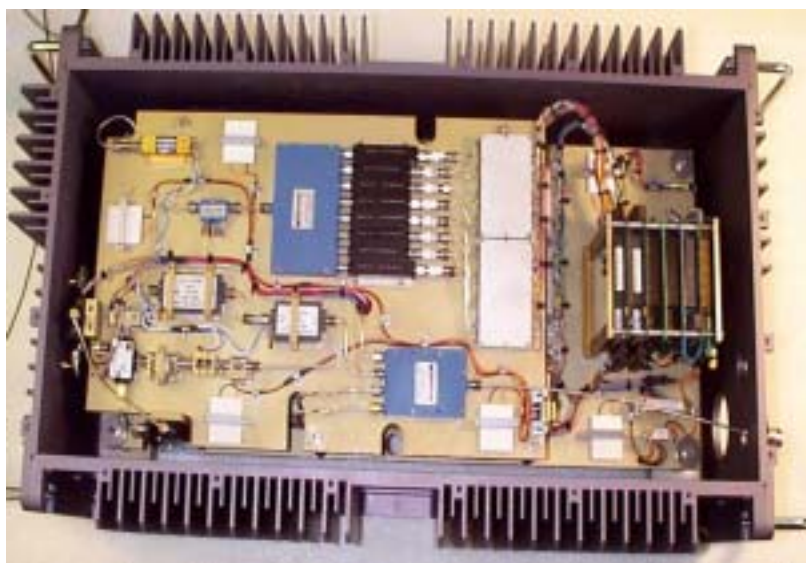
**Figure 1: Comparison of higher-order small slope and optical theories for emission from a bisinusoidal surface**

Figure 2 plots normalized backscattered field Doppler spectra obtained from a 1-D surface Monte Carlo simulation with the Watson-West non-linear hydrodynamic model [8] including the newly developed curvature filter [11]. Results at 5 m/s wind speed and at polar observation angles 40 and 80 degrees for HH and VV polarizations show broad Doppler spectra with visible features at both the positive and negative Bragg frequencies (indicated by the dashed vertical lines). Differences between the two polarizations are more apparent at the larger observation angle; detailed analysis of this data suggests that space-time localized high slope events can be a source of these differences.



***Figure 2: Normalized L-band backscattered field Doppler spectra from a Monte Carlo simulation with non-linear sea surfaces.***

Figure 3 is a photograph of the MFRAD receiver assembly. The system is currently producing useful data, and is available for future field experiments and for collaborative experiments with other researchers.



***Figure 3: Photograph of MFRAD receiver assembly***

## **IMPACT/APPLICATION**

Insights into emission physics are expected to have impact in methods for passive remote sensing of ocean wind vectors, needed in analysis of WindSAT data and in design and application of sensors for the NPOESS generation of weather satellites. The DURIP sensor can provide multi-frequency measurements of thermal emission for analysis of emission frequency dependencies. New insights into sea surface scattering will allow improved clutter reduction and active sea surface sensing methods to be created.

## **TRANSITIONS**

Results of the project have been communicated at several ONR sponsored workshops, including the ONR sponsored WindSAT program workshop.

## **RELATED PROJECTS**

Current related projects include:

1. An NSF sponsored project with Prof. Greg Baker (Math dept.) on development of hydrodynamic models
2. A NASA sponsored project on development of digital receivers for microwave radiometry

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